Understanding Long-Range Acoustic Propagation:
Theory and Numerical Simulations

Michael Wolfson
Applied Physics Laboratory
University of Washington
Seattle, WA 98105-6698
phone: (206)543-1320 fax: (206)543-6785 email: wolfson@apl.washington.edu

LONG-TERM GOAL

Our long-term goal is to contribute to the understanding of long-range propagation of sound in the ocean acoustic waveguide. The research effort concentrates on broadband acoustic transmissions that have not interacted with either the surface or bottom of the ocean. This effort intend to directly compliment the Long-range Ocean Acoustic Propagation Experiment (LOAPEX).

OBJECTIVES

We will attempt to formulate a predictive theory to address both the evolution with range of the fluctuation statistics of resolved ray/mode arrivals and the vertical structure of the deep shadow zone arrivals.

APPROACH

The long-range ocean acoustic propagation problem is essentially a problem dealing with weak, multiple forward scattering. Much of our approach in attacking this problem is based on numerical simulation and physical intuition. The intuition is primarily based on the knowledge that most of the sound speed variance is concentrated in the upper several hundred meters of ocean, and acoustic energy is expected to undergo most of its scattering via passage through the upper turning depths.

To test our models against reality, we suggested obtaining range dependent acoustic data by towing a low frequency source.   Our modeling results showed that due to low bandwidth and low signal-to-noise ratios, travel time sensitivity is not the optimal method for understanding the long-range multiple scattering problem. From our full-wave parabolic equation simulations using a background sound speed field typical of the eastern North Pacific Ocean through with sound speed fluctuations due to internal waves, we determined that the amount and 'shape' of depth scattering below a lower turning point caustic will give us a better chance at formulating a predictive theory for the evolution of all relevant observables as a function of range and acoustic frequency. As a bonus, measuring the range dependence of scattering by mooring a deep vertical line array of hydrophones and towing an acoustic source gives us an obvious path toward understand the deep so-called 'shadow-zone' arrivals which have been observed at SOSUS stations from prior long-range acoustic experiments.

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14. ABSTRACT
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The ONR project LOAPEX (Long-range Acoustic Propagation Experiment) [1] was performed in September/October of 2004, and it gratefully was able to accomplish what we needed.

WORK COMPLETED

Prior to the LOAPEX experiment, we demonstrated that aoustic ray trace models do not correctly describe the propagation at frequencies of order 120 Hz. This work was completed by first resorting to honest modeling, using an internal wave model based on the GM spectrum for internal waves, but without relying on the WKB assumption. More importantly, we discovered that high wavenumber internal waves cannot be neglected if one wants to correctly take into account the scattering physics. Indeed, we find t hat 80 vertical internal wave modes were necessary to include, and this causes ray trace methods to break down at ranges as short a single double loop length (< 50 km). We consider our results highly relevant to the long-range ocean acoustic community, since to date acoustic tomography relies on ray tracing to be correct. A theoretical explanation based on two different 'toy' models have been derived to lend insight into our findings. This work was in close collaboration with Frank Henyey, and a manuscript is in final preparation intended for submission to the Journal of the Acoustical Society of America. To summarize the fundamental result, the scattering strength, which is proportional to the acoustic frequency times the strength of the sound speed fluctuations times the length scale of the fluctuations, must be large in order that ray theory be valid. Obviously this is a singular limit.

Regarding the LOAPEX data, much initial progress has been made. We have received pulse compressed data at stations T50 through T1600 from Rex Andrew and Linda Buck at APL/UW.

We have examined the source motion and mooring corrections were supplied by Matthew A. Dzieciuch from Scripps. In going after the depth and 'shape' of the intensity distribution below particular lower turning depth caustics, we have determined that, to first order, these corrections can be neglected. Also, full-wave modeling through internal waves was performed, both by using independent and time-dependent internal wave realizations, giving us estimates of how much data will need to be used for obtaining this intensity distribution observable.

As for environmental data, we applied physically appropriate smoothing to the sound speed profiles derived from CTD casts which were taken at each LOAPEX source transmitting stations. Ray modeling (no internal waves) using these smoothed profiles was performed to identify particular lower turning depth caustics as a function of range. Additionally, this modeling is being used to discover possible processing problems.

Although much of this first order modeling is yielding comparisons to within 100 milliseconds of the impulse response data at each hydrophone, we are still in the process of testing and confirming our environmental data. Once this testing is complete, and the UCTD data is processed to obtain an estimate of the displacement variance of the internal waves, we will be ready to perform the full wave simulations through internal waves and predict the range dependence of the intensity distribution functions below particular lower turning depth caustics, which can then be compared to this same quantity derived from the data. Figure 1 shows our preliminary results regarding identifying arrivals in the data. Note only rays that did not interact with the surface or bottom are included.
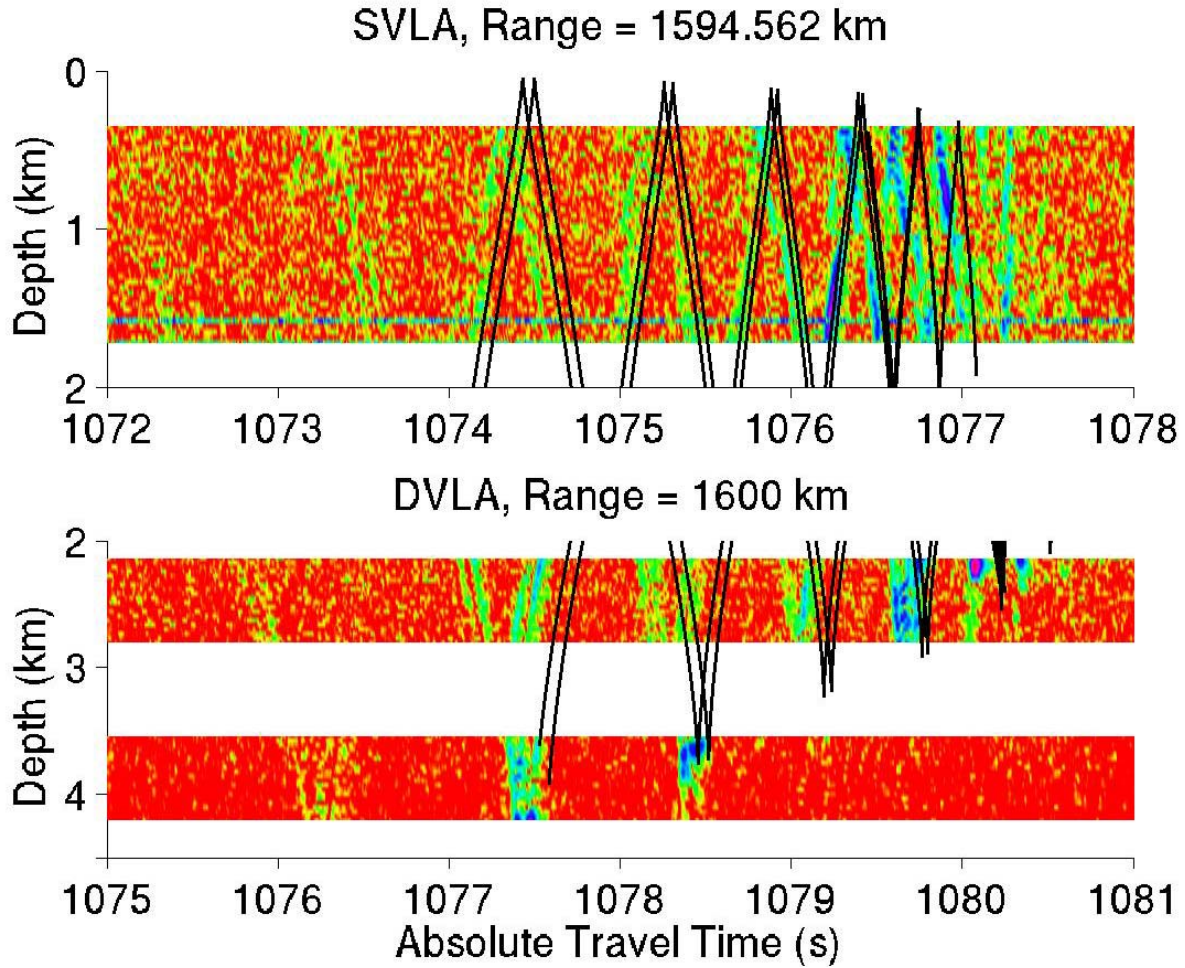
Figure 1. Acoustic intensity data from station T1600 for LOAPEX. The data is plotted with a 30 dB dynamic range (highest intensity dark blue, lowest magenta). A ray timefront is superposed in black. The LOAPEX source was deployed at 350 m depth with a carrier frequency of 68 Hz and 37 Hz bandwidth. The data shown was received at four sets of twenty hydrophones with nominal spacing of thirty-five meters.

RESULTS

Related to the objective described above concerns some results obtained regarding travel time bias due to horizontal refraction from internal waves. This work was a collaborative effort with Olig Godin and Valery Zavorotny of the NOAA lab in Boulder, Colorado. Briefly, Oleg derived a theory to include the effects of horizontal refraction on travel time into a two-dimensional formalism (standard range and depth coordinate system). The two-dimensional ray equations were modified to solve this problem required the horizontal derivative of sound speed fluctuations due to internal waves along the vertical plane connecting the source and receiver. We modified the APL/UW internal wave model to compute this quantity and performed extensive Monte-Carlo ray simulations on our APL/UW NPAL computer cluster. Results were presented at the Acoustical Society of America meeting in Minneapolis in 2005,

and we expect to submit a manuscript to the Journal of the Acoustical Society of America in early 2006. As an unexpected benefit, rigorous testing of our internal wave model was completed and we havemade it available to other researchers in the long-range acoustics community.

Some additional results were obtained regarding the mean field for long-range propagation. Basically, we propagated a pure acoustic mode (using a NPAL-like sound speed field) and observed how internal waves scattered the energy into neighboring modes. We determined that 1) the mean field is larger than its modal projection, and 2) the intensity does not decrease exponentially with range. Thus the unscattered mode is not a mode of the mean field. We found that intermediate acoustic modes (e.g. mode 20) is almost totally incoherent after only one hundred kilometers. This preliminary result related to an effort we are pursuing in developing a transport theory based on modes (without invoking the Dozier-Tappert assumption that the cross-mode coherence is small) was presented at the 2005 Acoustical Society of America meeting in Vancouver.

IMPACT/APPLICATIONS

We feel our work is leading toward the development of an efficient numerical model for predicting the behavior of wavefields as they evolve through random, weakly scattering wave guides.

RELATED PROJECTS

This work is related to the data analysis effort of LOAPEX.   With respect to obtaining environmental data, this work is related to the effort of the SPICE project.

REFERENCES

[1] Mercer et al. "Cruise Report: Long-range Ocean Acoustic Propagation Experiment (LOAPEX)," APL-UW TR 0501, April 2005.